

# Syn-subduction intra-continental shearing during Oligocene in Indochina, SE Asia

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## Abstract

Indochina developed continental-scale shear zones that record Cenozoic tectonic processes in SE Asia. Previous extrusion models that linked these shear zones with the northward indentation of the Indian continent, conflict with distributed conjugate strike-slip pairs and post-Oligocene rotation in Indochina. This paper presents evidence of coeval shearing along the Mogok-Shan Scarp fault in Myanmar, the western boundary of the Indochina block, previously proposed as a product of northward indentation of Indian Plate. The Kyanigan quarry along the northern Mogok-Shan Scarp fault exposes paragneiss, marble and quartzite schist. ‘ $\sigma$ ’ structures, cored with garnet, in paragneiss record right-lateral shear sense, consistent with ‘ $\sigma$ ’ and ‘ $\delta$ ’ structures in L-tectonites in the Moulmein granitic mylonite to the south. U-Pb ages of metamorphic zircons of paragneiss and a biotite 39Ar-40Ar age of quartzite schist constrain deformation in the Kyanigan quarry to 33–21 Ma; a biotite 39Ar-40Ar age of mylonite at Moulmein is 26 Ma. These ages demonstrate Oligocene right-lateral shearing along the Mogok-Shan Scarp fault, coeval with other shear zones in Indochina. These Oligocene shear zones and strike-slip faults are conjugate structures recording left-lateral shear sense on NW-striking and right-lateral shear sense on N-S to NE-striking features. After restoration of  $\sim 80^\circ$  clockwise rotation, the Oligocene conjugate strike-slip pairs in Indochina reflect approximate N-S-directed shortening, corresponding to northward subduction of the Indian ocean. This suggests that continental-scale intra-continental shearing may have been triggered by syn-subduction compression in SE Asia.

**Keywords:** Indochina; Oligocene; shear zone; intra-continental; syn-subduction

## 1. Introduction

Indochina, between the Tibet-Himalaya collisional orogen to the west and the active Myanmar-Indonesia subduction zone to the east, exposes continental-scale shear zones that record Cenozoic tectonic processes in SE Asia (Fig. 1a) (Leloup et al., 1995; Liu et al., 2006; Morley, 2001; Tapponnier et al., 1982; Tong et al., 2021; Xu et al., 2015; Zhang et al., 2017). These shear zones have been connected to an extrusion model, which proposed that Paleocene-Eocene Indian-Asian collision triggered SE-ward escape of Indochina, accompanied by clockwise rotation along boundaries of Oligocene Ailao Shan-Red River left-lateral shear zone to the east and right-lateral shearing Sagaing fault to the west (Fig. 1a) (Tapponnier et al., 1982).

Recent studies, however, challenged the extrusion model, by pointing out the following weaknesses:

(1) The extrusion model considered only the bounding faults of the Indochina region, such as the Ailao Shan-Red River shear zone and the Sagaing fault (Fig. 1a) (Tapponnier et al., 1982). However, coeval Oligocene strike-slip faults, including the bounding faults, are distributed throughout Indochina (Fig. 1b), and arranged in a conjugate pattern that may reflect E-W-directed compression, rather than SE-ward extrusion.

(2) The shear sense of some faults predicted by the extrusion model is contradicted by specific examples, such as the Jiali fault, Chongshan shear zone and Wangchao fault-Mae Ping shear zone (Fig. 1b). The Jiali fault is located close to Eastern Himalaya Syntaxis and was predicted to have right-lateral shear sense (Tapponnier et al., 1982), in contrast to the left-lateral shear sense observed in field studies (Lin et al., 2009; Zhang et al., 2020). The Chongshan shear zone was predicted to have a right-lateral shear sense along entire length (Tapponnier et al., 1982); however, detailed studies show that its north-middle segment records right-lateral shear sense, whereas south segment records left-lateral shearing (Fig. 1b) (Zhang et al., 2010). The Wangchao fault-Mae Ping shear zone has left-lateral shear sense (Lacassin et al., 1997; Österle et al., 2019), conflicting with the predicted right-lateral shearing as a “P” fracture (Tapponnier et al., 1982).

(3) The extrusion model predicted >700 km of escape of the Indochina block along the Ailao Shan-Red River shear zone (Leloup et al., 1995). However, based on reconstruction of extension in the Tonkin Gulf, Vietnam, Rangin et al. (1995) argued its left-lateral offset did not exceed 100 km (Fig. 1b).

(4) The extrusion model proposed that the Indochina block escaped SE-ward accompanied by Oligocene clockwise rotation (Tapponnier et al., 1982). However, recent paleomagnetic studies show that the ~80° clockwise rotation commenced at 25.7-17.3 Ma (Tong et al., 2016, 2021), younger than the predicted rotation age. Furthermore, some recent tectonic models argued that the terminal Indian-Asian collision happened at Miocene (25-20 Ma or 14 Ma) (van Hinsbergen et al., 2012; Xiao et al.,

2017), which are younger than the early stage of the Oligocene shear zones in Indochina. These models challenged the traditional extrusion model that assumed collision commenced in Paleocene-Eocene time (Tapponnier et al., 1982). These issues reflect uncertainty in the age of Indian-Asian collision and suggest the need to reexamine the geodynamic significance of Oligocene shearing in Indochina.

Conflicts between data and predictions of the extrusion model suggest the need for an alternative model to explain Oligocene tectonism in Indochina. The extrusion model assumed that the Sagaing fault marked the western boundary of the Indochina block (Fig. 1a) (Tapponnier et al., 1982), whereas this fault began activity at ca. 20 Ma as a transform fault of the Andaman Sea (Curray, 2005), younger than other Oligocene shear zones, suggesting that they are not products of the same tectonic event. The Mogok-Shan Scarp fault, east of the Sagaing fault, records ductile deformation in metamorphic rocks, and had been proposed as consequence of diachronous northward migration of Indian indentation (Fig. 1b) (Bertrand et al., 2001). In this paper, we will present evidence for coeval deformation along the Mogok-Shan Scarp fault, and review data on other Oligocene faults to propose an alternative model of syn-subduction intra-continental shearing in Indochina.

## 2. Regional Geology

SE Asia records the Tibet-Himalaya collisional orogen to the west and active subduction in the Indo-Burma-Indonesia belt to the east, between which is situated the Indochina block (Fig. 1a) (Tapponnier et al., 1982). The Indochina block exhibits distributed strike-slip faults, which are oblique to the paleo-suture zones of the Paleo-Tethys and Neo-Tethys oceans (Fig. 1b) (Lacassin et al., 1997; Leloup et al., 1995; Wang et al., 2006; Xu et al., 2012; Zhang et al., 2010, 2018, 2020).

The strike-slip faults from northwest to southeast can be divided into two groups (Fig. 1b). The first group of faults has left-lateral shear sense, and includes the Jiali fault (Lin et al., 2009; Zhang et al., 2020), Dongjiu-Milin fault (Xu et al., 2012), the southern segment of the Chongshan fault (Akciz et al., 2008; Zhang et al., 2010), the Ailao Shan-Red River Shear Zone (Leloup et al., 1995), the Wangchao Fault-Mae Ping Shear Zone (Lacassin et al., 1997; Österle et al., 2019) and the Klaeng Fault-Three Pagoda fault (Kanjanapayont et al., 2013; Nantasin et al., 2012). Another group has right-lateral shear sense, and includes the Medog shear zone (Dong and Xu, 2016), the Nabang fault (Wang et al., 2006; Xu et al., 2015), the Gaoligong fault (Wang et al., 2006; Xu et al., 2015), the northern segment of the Chongshan fault (Akciz et al., 2008; Zhang et al., 2010), the Mogok-Shan Scarp fault (Bertrand et al., 2001; Lamont et al., 2021; Searle et al., 2020, and this study), the Ranong fault (Watkinson et al., 2008, 2011), the Khlong Marui fault (Kanjanapayont et al., 2012b; Watkinson et al., 2008, 2011) and the Dien Bien Phu fault (Hung and Vinh, 2001; Tang et al., 2009). Movement along these faults have dated by zircon U-Pb, biotite and hornblende 39Ar-40Ar, K-Ar and Rb-Sr ages of

44.9-17.2 Ma from ductile shear zones, recording main stage movement of 31-23 Ma (Table 1), indicating Oligocene strike-slip movement.

41-23 Ma magmatic arcs occur along central Myanmar and Sumatra (Fig. 1), suggesting continuous oceanic subduction at that time in SE Asia (Bellon et al., 2004; Li et al., 2013, 2019; Mitchell, 1993; Searle et al., 2007; Xu, 2011). The Andaman Sea opened at 20 Ma (Fig. 1b) (Curry, 2005), and one of its transform faults continues northward on-land as the Sagaing Fault in Myanmar, which has ~ 400 km of right-lateral offset (Curry, 2005 and references therein). Paleomagnetic studies show that the Eocene-Late Oligocene strata in the Baoshan-Lanping-Simao basins have rotated ca. 80° clockwise, Middle Miocene (ca. 17.3 Ma) strata in the Baoshan basin have rotated 54° clockwise, whereas Late Miocene and Pleistocene strata in the Baoshan Basin have rotated only ~10° clockwise (Fig. 1b) (Tong et al., 2016, 2021). These data suggest that the Indochina block commenced crustal rotation during 25.7-17.3 Ma (Tong et al., 2021), younger than the early stage of Oligocene shearing.

### 3. Structural Geology

The Mogok-Shan Scarp fault along the western margin of the Indochina block preserves ductile deformation, east of the brittle Sagaing fault (Fig. 1b).

#### 3.1 Structures along the Mogok-Shan Scarp fault

The Mogok-Shan Scarp fault records primarily ductile deformation (Bertrand et al., 2001; Searle et al., 2020), including structures preserved in the Kyanigan quarry to the north and in Moulmein to the south (Fig. 1b).

The Kyanigan quarry exposures paragneiss, biotite quartzite, marble and leucogranitic dikes (Fig. 2a); paragneiss has fine-grained quartz-feldspar groundmass, and mm-cm-sized garnets (Fig. 3a-b). The foliation strikes 85-137° and dips northward (Fig. 2c). Thrusts are widespread, with paragneiss thrust over lower-grade marble (Fig. 2a), and shallow dipping (29°) biotite quartzite thrust over more steeply dipping (42°) rocks of the same lithology (Fig. 3c). Pressure shadows around cored garnet in paragneiss locally record right-lateral shear ‘ $\sigma$ ’ structures (Fig. 3b). A lineation in the paragneiss directs to E (Fig. 2c).

In Moulmein, mylonitic granites display horizontal N-S trending “L” tectonite (Fig. 4a), associated well developed ‘S-C’ fabrics, ‘ $\sigma$ ’ structures (Fig. 4b-c), micro-shear structures (Fig. 4b), and ‘ $\delta$ ’ structures (Fig. 4d). Micro-tectonics of a ‘ $\sigma$ ’ structure in mylonite show that feldspar underwent brittle fracturing and quartz recrystallized with development of 120° grain boundary intersections (Fig. 4e). Biotite grew parallel to foliation defined by oriented quartz (Fig. 4e). The

stretching lineations trend 180-160° with a sub-horizontal plunge (Fig. 2c). Asymmetric structures at multiple scales record right-lateral shear sense (Fig. 4).

In summary, lineations demonstrate the maximum stretch is subparallel to parallel to the direction of shearing, and structures along the Mogok-Shan Scarp fault were generated by right-lateral shearing (Figs. 3b, 4).

### 3.2 Structures along the Sagaing fault

The Sagaing fault is a brittle fault, an on-land continuation of a transform fault of the Andaman Sea to the south (Curry, 2005), and outcrops along its northern near the Yekha Lake include biotite quartzite and marble, similar to those in the Kyanigan quarry (Figs. 2a), granitic and dioritic dikes, and serpentinite (Figs. 1b, 2b).

Strikes of foliation of the quartzite and marble range from 80° to 187° (Fig. 2b-c), with most striking 80-153°, similar to those in the Kyanigan quarry (Fig. 2a, c). Some small-scale and short extended folds have E-W-trending hinges (Fig. 2b), which have been cut by the N-S-striking right-lateral Sagaing fault (Fig. 3d).

## 4. Ages of deformation

Garnet-biotite geothermometry and garnet-biotite-plagioclase-quartz geobarometry of paragneiss from the Kyanigan quarry constrained its pressures and temperatures of metamorphism to 0.77-0.84 GPa and 780-850 °C, respectively (Lamont et al., 2021; Ye Kyaw et al., 2016). We collected samples of a leucogranitic dike (14M88) and low-grade biotite quartzite (14M85) from the paragneiss. Zircons in sample 14M88 are larger than 100 µm, and have euhedral shapes with uniform internal textures (Fig. S1), suggesting their metamorphic features. They have been dated a zircon U-Pb age of  $33.1 \pm 0.8$  Ma (MSWD = 9.4, total 20 grains) (Fig. 5a), consistent with the metamorphic ages of garnet migmatites studied by Lamont et al. (2021). Low-grade biotite quartzite (sample 14M85) grew new metamorphic biotite and yielded a biotite 39Ar-40Ar age of  $20.9 \pm 0.8$  Ma (MSWD = 2.35) (Fig. 5b).

Micro-structure of the mylonite in Moulmein with brittle fracturing of feldspar and recrystallized quartz (Fig. 4e) suggests deformation temperature of 500-400°C, above Ar closure in biotite. This rock has yielded a biotite 40Ar/39Ar age of  $25.6 \pm 0.2$  Ma (MSWD = 1.50) (Fig. 5c) indicating Oligocene N-S directed right-lateral shearing.

## 5. Discussion

### 5.1 Deformation stages in Myanmar

The Mogok-Shan Scarp fault has been cut by brittle Sagaing fault (Figs. 1b, 2b, 3d), demonstrating that the Sagaing fault formed after metamorphism of the quartz schist at 20.9 Ma (Fig. 5b), younger than the proposed age of the Paleogene “Sagaing fault” in the extrusion model (Tapponnier et al., 1982).

The ‘ $\sigma$ ’ structures, cored by garnet in paragneiss in the Kyanigan quarry (Fig. 3b), suggests that shearing occurred between the formation of garnet paragneiss/leucogranite and biotite schist at 33.1 – 20.9 Ma (Figs. 5a-b) (Lamont et al., 2021, and this study). Right-lateral movement can drag and rotate earlier foliation. Therefore, we infer that the E-W and WNW-ESE-striking foliations and minor folds in schists (Fig. 2a-b) are products dragged from N-S trending structures by right-lateral shearing of the Sagaing fault (Swe, 2012; Zhang et al., 2018). Their original orientation would be consistent with that of the granitic mylonite in Moulmein (Fig. 4).

The deformation ages from shear zone rocks indicate that the Oligocene N-S trending ductile shear zone was contemporaneous from Mogok-Kyanigan in north to Moulmein in south (Fig. 1b, 5), rather than diachronous as a consequence of northward migration of the Indian indentation (Bertrand et al., 2001).

## 5.2 Oligocene faulting pattern in Indochina

From the Jiali fault in north to the Khlong Marui fault in south, and the Mogok-Shan Scarp fault in the west to the Ailao Shan-Red River fault in east, coeval Oligocene left- and right-lateral faults are distributed across Indochina (Fig. 1b, 6a).

Whereas some researchers assumed that the Jiali fault connected with the Ailao Shan-Red River shear zone (Leloup et al., 1995; Tapponnier et al., 1982), paleogeographic reconstructions show that they were separated by paleo-suture zones of the Paleo-Tethys Ocean and the Chongshan fault (Fig. 1b) (Zhang et al., 2020; Zhong, 1998). Zhang et al. (2020) suggested that the sinistral Jiali fault intersected the dextral Gaoligong fault, and they formed a conjugate strike-slip pair at the corner of the Eastern Himalaya Syntaxis.

The Chongshan shear zone has a similar conjugate pattern, with a N-S-striking northern segment exhibiting dextral shear sense, and the NW-SE-striking middle-southern segments showing sinistral shear sense (Fig. 1b, 6a) (Akciz et al., 2008; Tang et al., 2013; Wang et al., 2006; Zhang et al., 2010). This geometry reflected transpression-related shortening (Zhang et al., 2010), and conflicted with the extrusion model proposed identical shear sense along the entire shear zone at the early stage (Tapponnier et al., 1982). However, there was no documentation of dextral shearing in the middle-southern segments prior to sinistral shearing (Akciz et al., 2008; Tang et al., 2013; Wang et al., 2006; Zhang et al., 2010).

The left-lateral Ailao Shan-Red River shear zone is coupled with the right-lateral Dien Bien Phu fault at the eastern margin of the Indochina block (Fig. 1b) (Hung and Vinh, 2001; Tang et al., 2009). Similarly, faults along the western margin of the Indochina block demonstrate different shear sense on different segments (Fig. 1b), such as the dextral Mogok-Shan Scarp fault in north, transitioning to the sinistral Wangchao Fault-Mae Ping shear zone and Klaeng fault-Three Pagoda fault in middle, and to then dextral movement in south along the Ranong and Khlong Marui faults (Fig. 6a). Bertrand et al. (2001) accepted the extrusion model and assumed these faults recorded simple shear-related transpression during northward passage of the eastern Indian syntaxis. In their model the Wangchao fault-Mae Ping shear zone and Klaeng fault-Three Pagoda fault were be “P” fractures linked to the major Mogok-Shan Scarp fault (Bertrand et al., 2001; Tapponnier et al., 1982). This assumption, however, conflicts with the left-lateral shear sense recorded along these faults (Fig. 1b) (Ahrendt et al., 1993; Kanjanapayont et al., 2013; Lacassin et al., 1997; Morley, 2001; Österle et al., 2019).

Accordingly, some Oligocene faults in Indochina conflict with predicted shear sense of the extrusion model (Tapponnier et al., 1982), suggesting that they did not accommodate SE-directed escape. The sinistral faults mainly strike NE, whereas dextral faults strike N-S to NE (Fig. 1b, Table 1); they constitute huge conjugate strike-slip pairs (Fig. 6b) that accommodate N-S shortening (Zhang et al., 2014). This compression thickens continental crust to generate a 33-26 Ma gneiss dome with E-W vergence of asymmetric folds near Dali, northern Ailao Shan-Red River shear zone (Fig. 1b, 7b) (Zhang et al., 2014).

### 5.3 Syn-subduction intra-continental shearing at Oligocene

Extrusion-related models proposed that the Indian-Asian collision occurred in Paleocene-Eocene time (Leloup et al., 1995; Tapponnier et al., 1982). However, some alternative models proposed that the continental collisional age was as young as 25-14 Ma, based on evidence of paleomagnetic data and the youngest metamorphic ages of high-pressure metabasite (van Hinsbergen et al., 2012; Xiao et al., 2017). At 40-35 Ma the northern margin of the Indian continent (not the Great Indian Basin) located at ca. 10°N (Westerweel, 2020), and the Indochina block situated at ca.  $22.6 \pm 10.9^{\circ}\text{N}$  (Sato et al., 2001), suggesting they were separated by  $\sim 10^{\circ}$  at that time (Fig. 7a). These facts and associated model challenged the extrusion model, calling into question the relationship between Oligocene shearing and collision.

Paleomagnetic studies show that pre-Late Oligocene (ca. 25.7 Ma) strata in the Baoshan and Lanping-Simao basins underwent  $\sim 80^{\circ}$  clockwise rotation, and Middle Miocene (ca. 17.3 Ma) strata in the Baoshan basin rotated  $54^{\circ}$  clockwise (Fig. 1b) (Tong et al., 2016, 2021). These data suggest that the Indochina block commenced crustal clockwise rotation no earlier than 25.7 Ma, which is younger than the main stage of movement (31-23 Ma) of shear zones (Fig. 6a, Table 1).

We restored  $\sim 80^{\circ}$  clockwise rotation, paleo-latitude of tectonic units and the 20 Ma-opening of the Andaman Sea to obtain an Oligocene palinspastic map (Fig. 7a) that show long conjugate strike-slip pairs of ENE striking left-lateral shear zones coupled with WNW-striking right-lateral shear zones, and gneiss dome near Dali (Figs. 6b, 7b). This Oligocene faulting pattern appears to reflect approximate N-S-directed shortening (Fig. 7b). This new model is more compatible with the timing and shear sense of fault movement than Oligocene northward Indian indentation of the extrusion model, which accommodated the N-S shortening at the corner of the Eastern Himalaya Syntaxis (Dong and Xu, 2016; Xu et al., 2012; Zhang et al., 2014, 2020) and simple shear-related transpression to trigger southeastward escape of the main Indochina block (Leloup et al., 1995; Liu et al., 2006; Morley, 2001; Tapponnier et al., 1982; Zhang et al., 2010).

During the Oligocene, the Indian ocean subducted northward in SE Asia, and generated magmatic arcs along central Myanmar and western Sumatra (Fig. 1, 7a) (Bellon et al., 2004; Li et al., 2013, 2019; Mitchell, 1993; Searle et al., 2007; Xu, 2011), and folds and thrusts in the Indo-Burma Range and a gneiss dome near Dali that represents a compressional setting (Fig. 1b) (Hall, 2002; Zhang et al., 2014, 2018). We propose that syn-subduction compression affected the Indochina block of the upper plate to generate conjugate strike-slip faults with WNW-striking right-lateral and ENE-striking left-lateral shearing (Fig. 7b). Some strike-slip faults have relatively small offsets, such as that of the Ailao Shan-Red River shear zone, whose displacement is no more than a few tens of kilometers (Fig. 1b) (Rangin et al., 1995).

This new model explains not only the key features of previous models, but also features, such as different shear sense of different segments of the giant Chongshan shear zone. It further helps us to constrain Cenozoic tectonic evolution of SE Asia, and demonstrates that upper plate intra-continental shearing can be generated in a syn-subduction setting, comparable to modern western South America.

## 6. Conclusion

Based on our field mapping, structural and geochronological analyses, integrated with published data, we draw the following conclusions:

- (1) The 26 Ma asymmetric structures in L-tectonites in the Moulmein granitic mylonite are consistent with those in the Kyanigan paragneiss, formed at 33-21 Ma, indicating coeval right-lateral shearing along the Mogok-Shan Scarp fault in Myanmar.
- (2) Oligocene shear zones and strike-slip faults are distributed across the Indochina block. These faults exhibit sinistral shear sense on NW-striking faults and dextral shear sense on N-S to NE-striking, constituting conjugate strike-slip pairs.
- (3) After post-Late Oligocene restoration of clockwise rotation, paleomagnetic data and opening of the Andaman Sea, the Oligocene conjugate faulting pattern in Indochina demonstrates an approximate N-S-directed compression, corresponding to northward subduction of the Indian ocean. The syn-subduction compression triggered intra-continental shearing in SE Asia.

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## **SUPPORTING INFORMATION**

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### Figure Legends

Figure 1 (a) Simplified structural map of southeast Asia showing shear zones in Indochina, which had been proposed as boundary faults accommodating SE-ward escape driven by Indian-Asian collision in the extrusion model (Modified after Tapponnier et al. (1982)). (b) Shaded relief map showing Oligocene strike-slip faults, shear zones and magmatic arcs in Indochina, paleo-suture zones and active subduction zone/thrust zones. Magmatic arcs are based on Bellon et al. (2004), Li et al. (2013, 2019), Mitchell (1993), Searle et al. (2007) and Xu (2011). Paleo-suture zones and active subduction zone are based on Zhang et al. (2018). Paleomagnetic data in the Baoshan-Lanping-Simao basins are from Tong et al. (2016) and Tong et al. (2021). Age of the Andaman Sea (20 Ma) is marked (Curray, 2005). 33-26 Ma dome-related lineation is based on Zhang et al. (2014). Locations of Fig. 2a-b, 4, and dated sample 14M07 have been marked.

Figure 2 Geological maps of (a) the Mogok-Shan Scarp fault in the Kyanigan quarry, showing E-W-striking paragneiss thrust over lower grade metasediments, and (b) the brittle Sagaing fault near Yekha Lake, cutting E-W/WNW-ESE-striking metasediments and minor folds with E-W-trending hinges. Locations of Fig. 3a, c-d and samples 14M85 and 14M88 are marked. (c) Stereonet diagrams plotting attitude of foliations of metasediments and paragneiss, and orientation of the Sagaing fault. The stretching lineations from the Kyanigan quarry and Moulmein have been plotted.

Figure 3 Photos showing (a) ESE-WNW striking paragneiss in the Kyanigan quarry and (b) right-lateral shear sense associated with ‘σ’ structure cored by garnet. (c) A thrust in biotite quartzite schists. Locations of dated samples 14M85 and 14M88 are marked. (d) Photo showing the N-striking brittle Sagaing fault cutting E-striking metasediment near Yekha Lake, suggesting the brittle fault was younger than deformation of the schist.

Figure 4 Photos of the N-S trending granitic mylonite in Moulmein, showing (a) horizontal L-tectonite, (b) minor ductile shear fault, (c) ‘σ’ structure and (d) ‘δ’ structure. These structures consistently show

right-lateral shearing. (e) Microstructure of granitic mylonite in Moulmein showing ‘σ’ structure with right-lateral shear sense. The feldspar underwent brittle fracturing, and quartz developed recrystallized sub-grains, suggesting their deformation temperature at ca. 400-500°C. The oriented biotites are syn-tectonic products that are used to constrain the deformation age of mylonite.

Figure 5 (a) Metamorphic zircon U-Pb age of a leucogranitic dike in the paragneiss and (b) biotite 39Ar-40Ar age of low-grade quartzite in the Kyanigan quarry, representing the ductile deformation ages of 33.1-20.9 Ma. (c) biotite 39Ar-40Ar age of granitic mylonite in Moulmein, demonstrating granite underwent right-lateral shearing in the Oligocene.

Figure 6 (a) Ages of strike-slip faults in Indochina showing their main occurrence at 31-23 Ma. Detailed deformation ages, shear sense and references are presented in Table 1. The main stage of shearing is coeval with magmatic arcs, and prior to those of the large-scale clockwise rotation of Indochina and Andaman Sea. (b) Rose diagram showing Oligocene WNW-ESE-striking left-lateral faults and N-S/NNE-SSW-striking right-lateral faults in Indochina; they constitute conjugate strike-slip pairs. ‘σ1’ represents the maximum principal stress.

Figure 7 (a) Palinspastic map of Oligocene paleo-locations of units in SE Asia after restoration of post-Oligocene 88-54° clockwise rotation (Tong et al., 2016, 2021) and the Andaman Sea (20 Ma) (Curry, 2005), showing that magmatic arcs and the Indochina block located to ~10° north of the northern margin of the Indian continent (not the Great Indian Basin) at 40-35 Ma (Sato et al., 2001; Westerweel, 2020), and the Indochina block extended to E-W or WNW-ESE. (b) Schematic map showing Oligocene conjugate strike-slip shear zones in Indochina and a gneiss dome near Dali that were generated by N-S compression. The faulting pattern is different from that of the extrusion model, in which transpression generated simple shear-related SE extrusion of the Indochina block accompanying clockwise rotation in the Oligocene as shown in Figure 1a. Acronyms of faults are: ARSZ: Ailao Shan-Red River shear zone; CSF: Chongshan fault; DBPF: Dien Bien Phu fault; GLF:

Gaoligong fault; JLF: Jiali fault; KMF: Khlong Marui fault; MPSZ: Wangchao fault-Mae Ping shear zone; SSF: Mogok-Shan Scarp fault; TPF: Klaeng fault-Three Pagoda fault.

## Figures

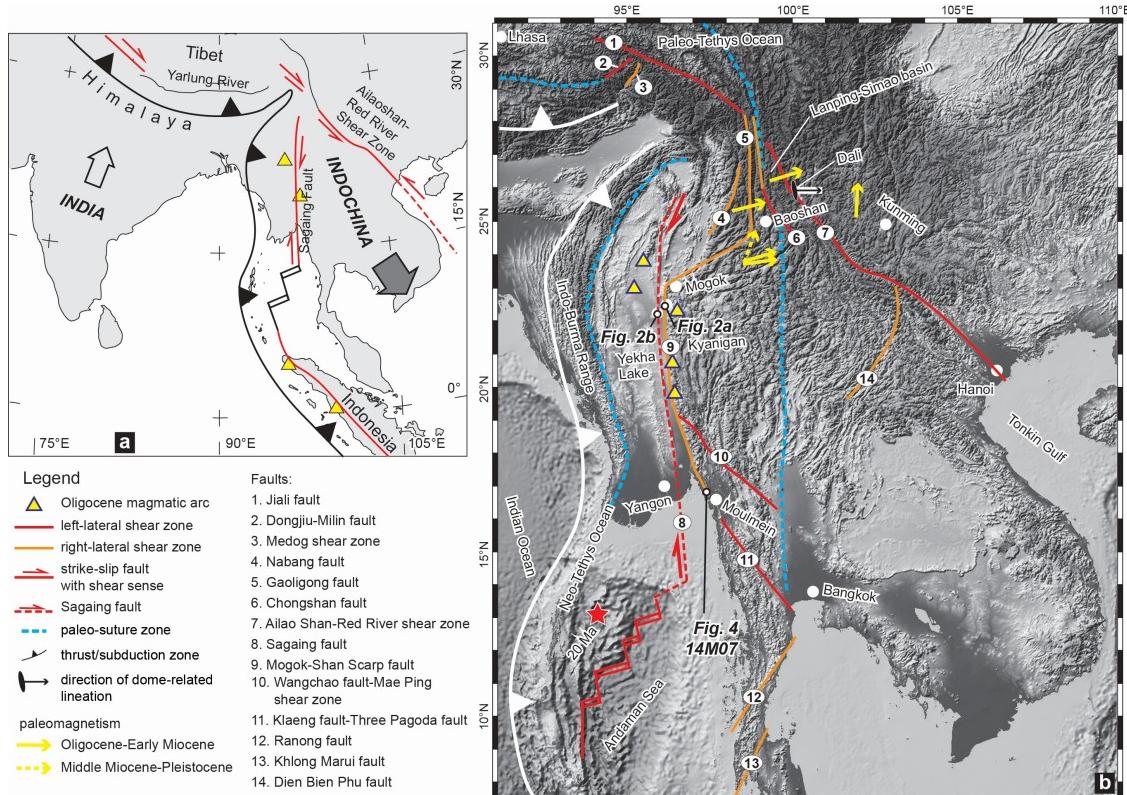


Figure 1 Zhang et al., 2021

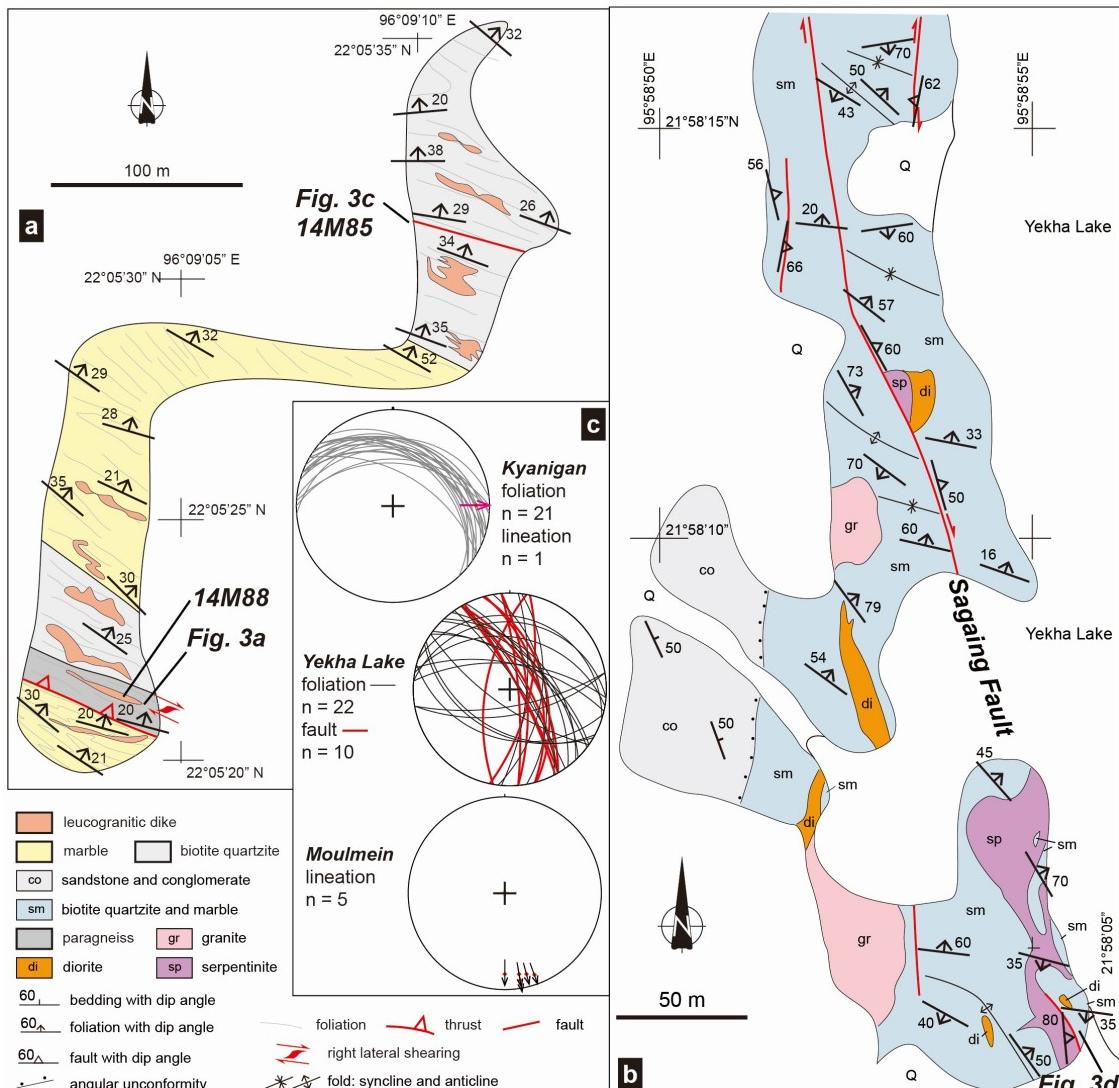


Figure 2 Zhang et al., 2021

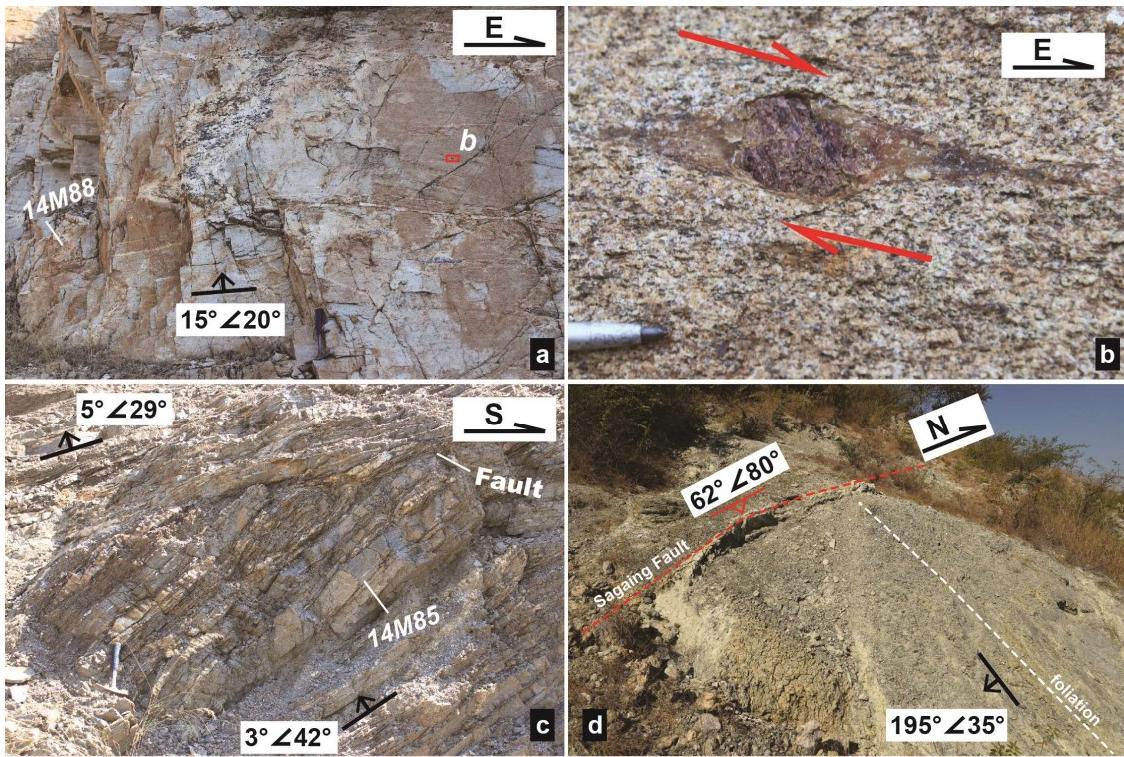


Figure 3 Zhang et al., 2021

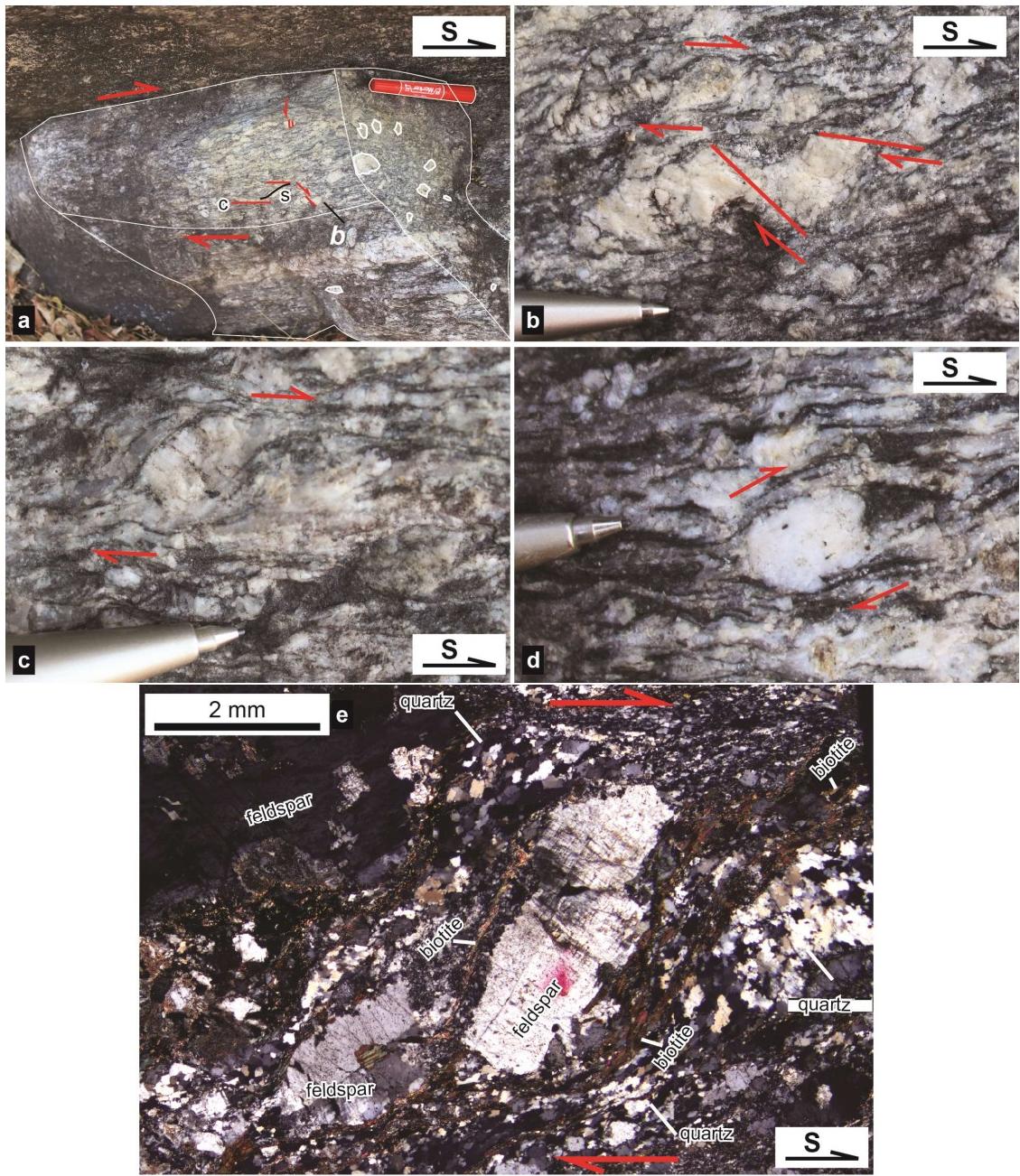


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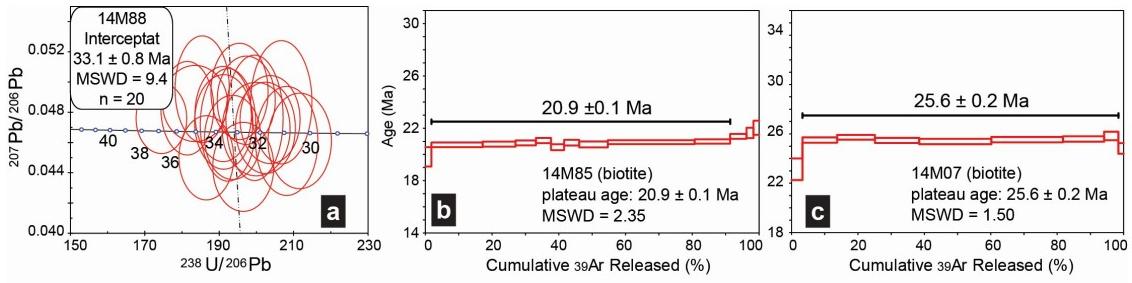


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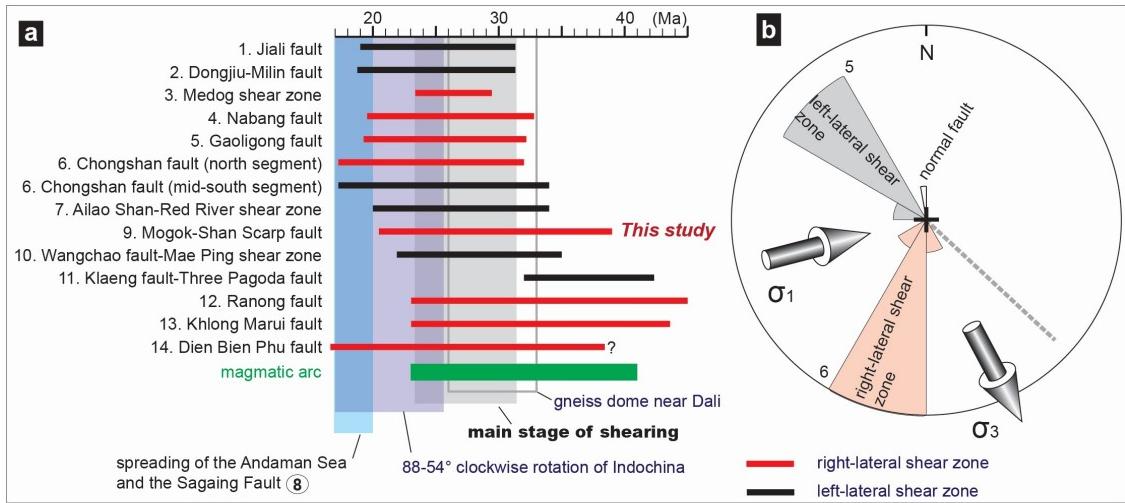


Figure 6 Zhang et al., 2021

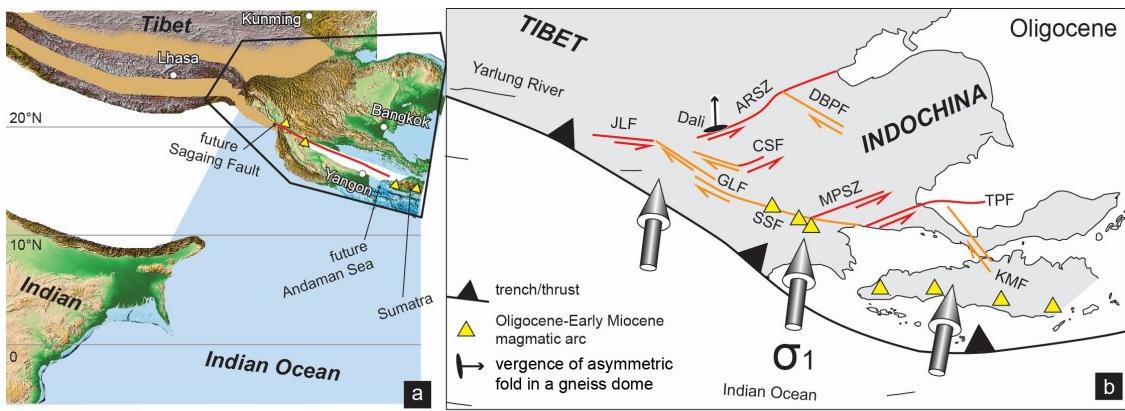


Figure 7 Zhang et al., 2021

## Tables

Table 1 Properties of Oligocene shear zones in Indochina

Fault name	Strike	Shear sense	Ages (Ma)	References
Jiali fault	WNW	L	31.4-19 ▲	Zhang et al., 2020
Dongjiu-Milin fault	NE	L	31.3-18.7▲·◊	Xu et al., 2012
Medog shear zone	SSW	R	29.3-23.4 ▲·◊	Dong and Xu, 2016
Nabang fault	SSW	R	32.8-19.5 ▲	Wang et al., 2006; Xu et al., 2015
Gaoligong fault	N-S	R	32.1-19.3 ▲	Wang et al., 2006; Xu et al., 2015
Chongshan fault-north	N-S	R	32-14 ▲·◊	Akciz et al., 2008; Zhang et al., 2010
Chongshan fault-south/middle	NNW	L	34-17.2 ▲·◊	Akciz et al., 2008; Tang et al., 2013; Wang et al., 2006; Zhang et al., 2010
Ailao Shan-Red River shear zone	NW	L	34-20 ▲·◊	Cao et al., 2011; Leloup et al., 2001; Leloup et al., 1995
Sagaing fault	N-S	R	<20.9 ▲	<b>This study</b>
Mogok-Shan Scarp fault	NNW	R	39-20.9▲·◊·■	<b>This study</b> , Bertrand et al., 2001; Searle et al., 2020
Wangchao fault-Mae Ping shear zone	NW	L	35-22 ▲·◊·■	Ahrendt et al., 1993; Lacassin et al., 1997; Morley et al., 2001; Otofuji et al., 2012
Klaeng fault-Three Pagoda fault	NW	L	42.5-32 ♦	Kanjanapayont et al., 2012b; Nantasin et al., 2012
Ranong fault	NE	R	44.9-23 ▲	Watkinson et al., 2008, 2011
Khlong Marui fault	NE	R	43.6-23 ▲·♦	Kanjanapayont et al., 2012a; Watkinson et al., 2008, 2011
Dien Bien Phu fault	NE	R	Mid-Late Paleogene - 5.8 ○	Hung and Vinh, 2001; Tang et al., 2009

Note: Shear sense: L: left-lateral shear sense; R: right-lateral shear sense. Dating method: ▲ biotite-mica-hornblende  $^{39}\text{Ar}$ - $^{40}\text{Ar}$ , ◊ zircon U-Pb, ■ biotite-feldspar K-Ar, ♦ Rb-Sr, ○ sediments. More details see the Table S5.